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Review

Coastal Morphodynamics and Climate Change: A Review of Recent Advances

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Abstract: The shape of the coast and the processes that mold it change together as a complex system. There is constant feedback among the multiple components of the system, and when climate changes, all facets of the system change. Abrupt shifts to different states can also take place when certain tipping points are crossed. The coupling of rapid warming in the Arctic with melting sea ice is one example of positive feedback. Climate changes, particularly rising sea temperatures, are causing an increasing frequency of tropical storms and "compound events" such as storm surges combined with torrential rains. These events are superimposed on progressive rises in relative sea level and are anticipated to push many coastal morphodynamic systems to tipping points beyond which return to preexisting conditions is unlikely. Complex systems modeling results and long-term sets of observations from diverse cases help to anticipate future coastal threats. Innovative engineering solutions are needed to adapt to changes in coastal landscapes and environmental risks. New understandings of cascading climate-change-related physical, ecological, socioeconomic effects, and multi-faceted morphodynamic systems are continually contributing to the imperative search for resilience. Recent contributions, summarized here, are based on theory, observations, numerically modeled results, regional case studies, and global projections.

Keywords: sea level rise; land loss; coastal inundation; wetlands; estuaries; Arctic coasts; coral reefs; compound flooding; complex systems; morphodynamic processes; tipping points

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1. Introduction

In coastal "morphodynamic" systems, the shapes of the solid surfaces (shores, wetlands, estuaries, continental shelves, etc.) and the processes that mold the changing morphologies are mutually interconnected and change together [1–10]. Such systems interconnect hydrodynamic, biologic, and anthropogenic processes with coastal and seafloor landscapes, including the foundations on which most coastal communities rest. Temporal sequences of change involve the entire system. Coastal morphologies and their controlling process regimes, which today include engineered infrastructure, co-evolve over both short and prolonged periods of time. It is understood that climate change is now inducing changes in coastal processes and morphologies that are superimposed on those caused earlier by natural and human-induced processes. Because there is constant feedback among the multiple components of the system, when environmental conditions change, all facets of the system also change.

Causative physical and biological process regimes and morphologic patterns co-evolve over time, and mutual causality involves feedback loops that may be either positive (self-enhancing) or negative (self-regulating). Sequential changes are not always gradual or progressive. Abrupt shifts to different states can also take place when certain equilibrium thresholds, or "tipping points" [11], are crossed, leading to short-lived episodes of positive feedback. To effectively anticipate and plan for the changes in coastal morphologies that result from new patterns of erosion and deposition that climate change is likely to cause, we must first understand the current and inherited morphodynamic systems to contribute to evolving adaptation strategies. Projections of likely future conditions involve analyses of observed trends, advanced numerical and theoretical modeling, and comprehensive literature syntheses.

Assessments of the latest understandings of climate change and its impacts are periodically updated by the US Global Change Research Program via the National Climate Assessment Reports (NCA) [12]. The Fourth National Climate Assessment was published in 2017. The latest report (NCA5) was released in 2023 [13]. That definitive report emphasizes that coastal hazards are increasing because of rising sea levels, increased storminess, and storm-induced high waves and surges. Rising sea surface temperatures are the primary source of these destructive processes. The Intergovernmental Panel on Climate Change (IPCC) is a definitive source of current scientific consensus on the causes and consequences of global change. Their sixth report, published in 2022 [14], presents exhaustive and conclusive evidence that air temperatures at the earth's surface as well as sea temperatures are rising, leading to a host of other harmful climate and ocean changes.

Predicting the future impacts of climate-induced changes in coastal processes on coastal morphologies and ecosystems requires complex systems models [15–18] that account for a hierarchy of interconnections and non-linear feedback. Extended time series of observations are needed to verify the models and to provide input into testing assumptions and understanding local and regional conditions where models are to be applied. Some progress is already being made in this area; however, to enable transformational advances, the scientific community needs to further advance understanding of the interconnectedness of morphodynamic and socio-ecological systems, including beaches and sandy coasts, wetlands, deltaic coasts, muddy coasts, Arctic coasts, continental shelves, coral reefs and reef islands, and built infrastructure. This brief review describes some of the recent advances that could serve as building blocks for a new generation of understandings and strategies that we expect to be imminent. New perspectives that are emerging or have recently been reported are highlighted.

2. Coastal Inundation and Climate Change

Climate change is increasing the inundation of coasts, particularly low-elevation coasts, on many spatial and temporal scales. Long-term rises in global sea levels on decadal time scales as well as interannual sea level fluctuations and localized, short-lived flooding events are largely attributable to increasing sea surface temperatures. A recent comprehensive NOAA report [19] states, with high confidence, that "By 2050, the expected relative sea level (RSL) will cause tide and storm surge heights to increase and will lead to a shift in U.S. coastal flood regimes, with major and moderate high tide flood events occurring as frequently as moderate and minor high tide flood events occur today." "Without additional risk-reduction measures, U.S. coastal infrastructure, communities, and ecosystems will face significant consequences". The NOAA report predicts that between now and 2050, US mean sea levels will rise an additional 0.25–0.30 m. In many localities, the relative sea level rises will be significantly greater because of land subsidence and other non-tidal effects such as reductions in the strength of the Atlantic Meridional Overturning Circulation (AMOC) [20,21]. At the present time, the global averaged rate of mean sea level rise is 3.3 mm/yr but is accelerating [19]. Rates of rise significantly exceed the global average in many localities for a variety of reasons. Since 1993, the rates of sea level rise over most of the western Pacific, including most of the Australian coast, have exceeded the global rate. https://soe.dcceew.gov.au/climate/environment/sea-level (accessed on 30 August 2023).

From a morphodynamic standpoint, it is not so much the global rises in mean sea level that dominate the short-term flooding of coasts and associated shoreline fluctuations as the storm surges and powerful storm waves that are superimposed on the rising seas. Fueled by increasing sea surface temperatures, compound floods involving combined storm surges and torrential rains are becoming more frequent and severe. Sea level rises are exacerbating coastal recessions by allowing the landward penetration of destructive waves [22]. Increasingly, new international research is being directed at the nature and impacts of complex and protracted disasters that are compounding and cascading [23]. A prominent recent example was the devastating impacts of Hurricane Ian on southwest Florida in September 2022. The joint probability of severe storm surges and torrential rains coinciding in U.S. coastal cities has increased significantly over the past century [24–26]. In cases where rivers are nearby, fluvial flooding further exacerbates the severity of the inundation [27]. A recent analysis downscaled multiple hurricane models to create a synthetic model that predicts that climate change is increasing hurricane risk for the Gulf Coast and Atlantic Coast [28]. The International Human Dimensions Program on Global Environmental Change points out that by midcentury, the flood risk to large coastal cities will have increased by ninefold relative to the present day. According to NOAAs Office of Coastal Management, inundation events are the dominant causes of natural-hazard-related deaths in the U.S. and are also the most frequent and costly of the natural hazards affecting the nation. The landward penetration of destructive storm waves into the floods can erode and redistribute large quantities of sediment in short periods of time, resulting in significant changes in coastal morphology. This can amplify or otherwise alter the behavior of surges.

At both long-range and event time scales, significant advances are progressively being made in modeling storm surges, storm waves, and coastal circulation. One of the simplest and lowest resolution models is NOAAs operational two-dimensional Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. The academic community uses more accurate, unstructured grid models of coupled surge-wave effects [29]. Although those models yield better results than the operational, long-standing two-dimensional SLOSH model used by NOAA for several decades, SLOSH continues to be the operational model of choice because it is well accepted, fast, and does not require High Performance Computing or HPC (advanced computing) resources. NOAA has recently upgraded its Probabilistic Slosh model, named P-Surge, to version 3 [30]. Figure 1 shows a U.S. National Hurricane Center prediction of storm surge heights associated with landfalling Category 4 Hurricane Ian on the coast of South Florida on the U.S. Gulf of Mexico on September 28, 2022, based on output from NOAAs SLOSH storm surge model.

For timely, rapid forecasts of impending surges, updated P-Surge versions of SLOSH are likely to remain the operational standard for the near future. However, for anticipating potential, but not impending, future scenarios, more advanced and time-consuming models that utilize HPC resources are the current state of the art. Some of the more widely used models are described in [29,31–33]. Storm surge and wave modeling, together with tidal modeling, are essential for coastal erosion/deposition and coastal inundation estimates. A recent NOAA-IOOS-funded Coastal Ocean Modeling Testbed (COMT) program [29,33], involving over 20 academic institutions as well as several federal research centers, focused on improving forecasts of coastal waves, storm surges, and inundations. Included among the six models evaluated was the well-known three-dimensional, finite element Advanced Circulation (ADCIRC) [34] model, which was coupled with the Simulating Waves Nearshore (SWAN) wave prediction model developed by the Delft University of Technology. Additional models that may be applied to surge and wave modeling include Delft3D, WAVEWATCH III®, and GeoClaw.

The ADCIRC model was utilized by [35] in an assessment of the probable impacts of climate change on storm surges affecting the US coasts. That study concluded that volumes of flood waters from US Gulf Coast and Atlantic Coast storm surges are increasing and are expected to continue to increase and become more severe in the years ahead. The authors also point out that future storm surge severity and impacts will be difficult to predict. Challenges facing reliable projections of future impacts include the complex interdependence of spatially variable storm characteristics and coastal configurations linked to changing regional patterns of sea surface temperatures, which will require probabilistic assessments. The morphodynamic interdependence of nearshore morphology and the spatiotemporal variability of winds, surges, and waves represents an important area for future research and model development. Some insightful studies in eastern Australia have highlighted these interdependent relationships [36].

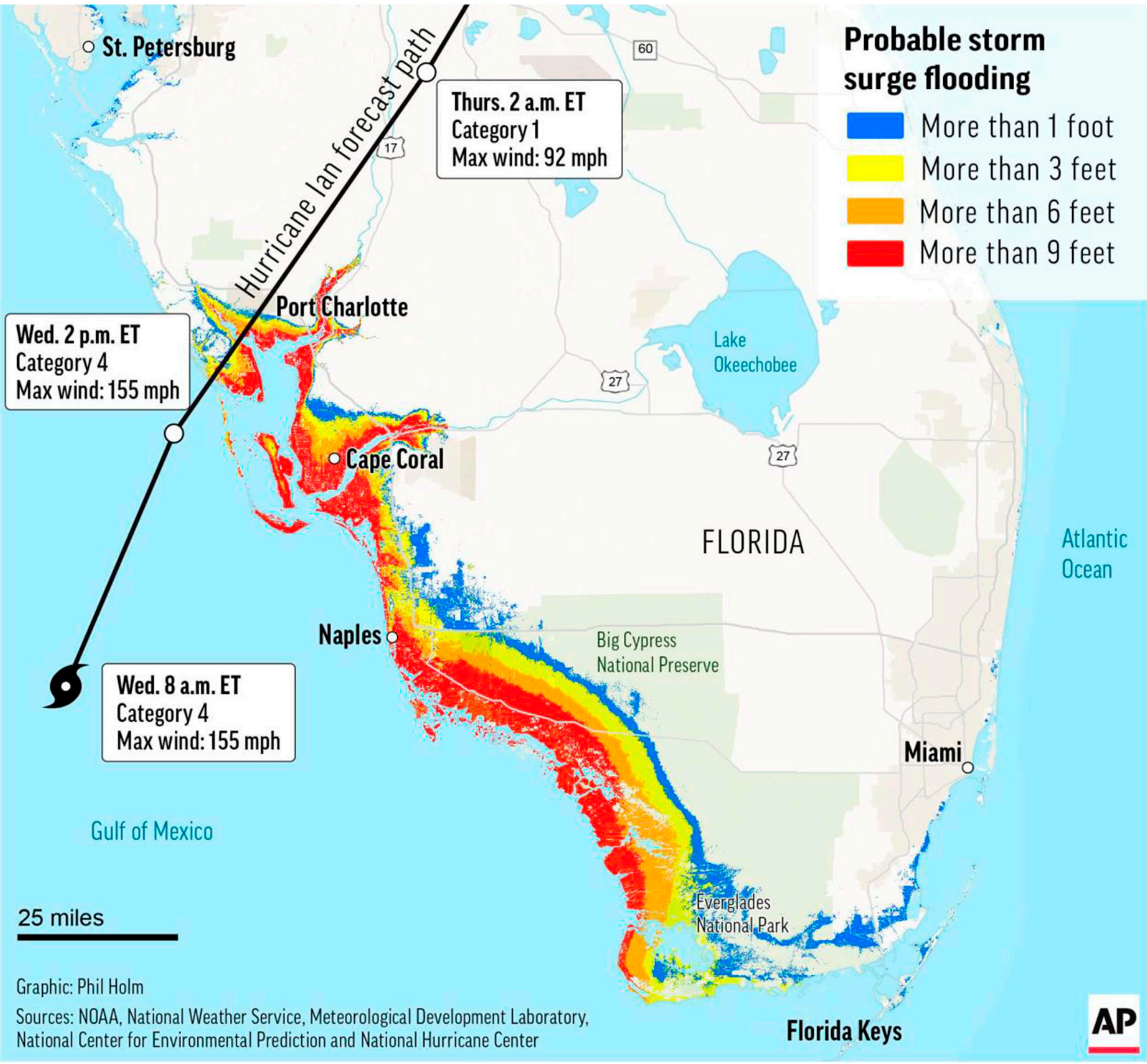

Figure 1. National Hurricane Center predictions of storm surge inundation utilizing NOAA's SLOSH model of the "maximum of maximum envelopes of water" (MOMS) associated with landfalling Category 4 Hurricane Ian on the South Florida Coast on 28 September 2022. Inundation of the red areas was predicted to exceed 9 feet (~3 m) above existing ground levels. Source: NOAA National Weather Service.

3. Tipping Points in Coastal Systems

Physical, environmental, socioeconomic, and engineered changes in coastal areas interact, often in unforeseen ways that may involve positive feedback, leading to a tipping point at which one more small change results in a large destabilization [11,37–39]. At this point, the environmental system can enter a new state beyond which recovery to earlier conditions may be unlikely. Based on insights from multidisciplinary analyses of the Santa Barbara, CA, coast [36], it was concluded that the tipping point for serious degradation of beaches and wetlands could be crossed when sea level rises reach 0.25 m or even less. In the case of the morphodynamics of river deltas, a recent study of historical delta evolution showed that the rate of rise of relative sea level (including subsidence) tipping point for delta accretion to keep pace with submergence has been about 5 mm/yr [39]. Today, however, the severance of sediment supply to the coast by dams on rivers has probably lowered that critical tipping point in many cases. Once the tipping point has been exceeded, delta growth cannot keep pace with more rapid rates of SLR, and open water will replace dry land [39,40]. In a study of tidal salt marsh equilibrium [41], it was found that marsh growth can keep pace with rising relative sea level at rates up to 1.2 cm/yr; however, when the rate of rise exceeds that critical tipping point, subaerial marsh surfaces are replaced by tidal flats. The concept of tipping points can be applied where communities along the coast are subject to a variety of mounting pressures resulting from ongoing coastal land loss and inundation [42]. However, we must take care not to simply extrapolate on determinations of SLR tipping points from one study to another without understanding past and present morphodynamic processes that control morphologies and sediment budgets in the area of concern. Time lags of varying durations typically exist in shoreface adjustment of boundary conditions due to changes such as SLR and can involve long morphological-response timescales across the lower shoreface [43].

A somewhat less well-known but emerging potential tipping point affecting the entire Atlantic coast of North America involves the Atlantic Meridional Overturning Circulation (AMOC), of which the Gulf Stream is a part. Variability in Gulf Stream flow drives short-term coastal sea level shifts of 70 cm or more. The Gulf Stream influences coastal sea levels on Florida's east coast and extends along the mid-Atlantic coast and northward [20,21,44]. Recent analyses [21,45] suggest that AMOC may be close to a tipping point for transitioning to its weak circulation mode. A major weakening or shutdown of the Gulf Stream could result in significant sea level rise along much of the Atlantic coast, particularly south of Cape Hatteras. The most recent publication on AMOC [21] suggests that this tipping point could be crossed at any time after 2025. Research and review papers on other far-reaching tipping points affecting significant shifts in coastal morphodynamic regimes will be important in long-range planning.

4. Coastal Erosion and Shoreline Transgression

Coastal morphologic changes typically involve erosion in some places and accretion in other places. In the classic literature on beach behavior, it was understood that, typically, during storms or other high-energy events, waves move large volumes of beach and surf zone sand seaward to depths of 20 m or more in short periods of time. After the event subsides, the sands are slowly returned to the beach by low, long-period swells. This volatility is cyclic and seldom involves permanent land loss unless the section of coast is, for natural or human-induced reasons, starved of sediment. Climate change now has the potential to cause irreversible recession in many coastal regions and is displacing whole communities in many cases [46,47], particularly on muddy coasts and deltaic coasts. The superimposition of high waves and storm surges during tropical and extra-tropical storms can cause landward translations of the surf zone, often well into seaside communities, as was recently the case when Hurricane Ian made landfall near Ft. Myers, Florida. Even where no net-long recession is apparent, increased storm severity and surge intensity cause increases in the distance inland that storms penetrate.

As storms become more intense and sea level rises, eroded sediments are transported offshore to greater depths beyond the reach of fair-weather waves and may not return to the beach or may return more slowly than in the past. As is known from historic and geologic studies, shoreline recession can extend over broad lengths of coast. Sand barriers have evolved during the Holocene (and in places in previous interglacials) because of marine transgressions associated with post-glacial SLR. A well-documented example is the Danish North Sea coast, where shoreline recession took place at rates of SLR of 8.6 mm/yr. [48]. Progradation occurred when abundant sediment became available, even with a declining rate of SLR. However, on other coasts, a rate of SLR as little as 2 mm/yr was seen as the threshold value between coastal transgression and regression [49]. A recent comprehensive analysis of the coasts of the UK and Ireland [50] showed that a large proportion of that extensive coast is eroding because of a combination of rising sea levels, reduced sediment supply, and human interference. Such erosion has been ongoing for centuries in some sections, given its glacial and post-glacial history, affecting land and seabed sediment supplies and types. Another recent UK-based study concluded that erosion is not limited to sandy or soft sediment coasts but is also impacting rocky coasts because sea level rise is allowing storm waves to reach the cliffs more often [51].

In contrast to the conclusions reported in [22], a recent analysis of the observed behavior of Australian beach systems concludes that many have been stable for several decades and may not be threatened by climate change [52]. From a notable recent analysis of a 50-year time series of monthly beach surveys of a high-energy beach system on Australia's New South Wales Coast [53], it was concluded that while there has been no long-term net coastal recession, beach fluctuations that occur reflect patterns of storminess and the capacity of the beach to recover in post-storm periods. Consistent with these Australian studies, a recent analysis of global trends in changing wave intensity and related shoreline behavior [54] reports that "Over the past 30 + years, we show that there have been clear changes in waves and storm surge at global scale. The data, however, does not show an unequivocal linkage between trends in wave and storm surge climate and sandy shoreline recession/progression." Understanding the reasons for these results could provide insights relevant to future adaptation. In addition, the role of global atmospheric systems such as ENSO in influencing large regional variability in coastal erosion and accretion, as recently documented along the Pacific Rim, must be factored into any understanding of shoreline variability [55].

A multi-scale Probabilistic Coastline Recession (PCR) model was applied by [22] to swell-dominated Narrabeen Beach near Sydney, Australia, and storm-dominated Noordwijk aan Zee Strand, The Netherlands. The model estimates the magnitude of coastline recession caused by the combination of sea level rise, storm waves, and storm surge over a prolonged period (~100 years). The results suggested that sea level rise likely plays the dominant role in the long-term recession of both types of beach regimes. Long-term changes in wave climate were predicted to have only marginal impacts on recession. It should be pointed out, however, that this model-based conclusion may not apply to coasts such as the US Gulf Coast and East Coast, where tropical cyclones are becoming larger and more intense and storm surges are becoming higher and reaching farther inland [43]. A contrasting conclusion from the Australian east coast resulted from an evaluation of changes in wave climate over a centennial time scale in relation to sediment sources and sinks and provides a range of challenges in understanding the interaction of processes leading to future shoreline transgression [36]. More on this subject follows in the next subsection.

Narrow barrier islands, backed by open-water lagoons or tidal wetlands, are common along much of the U.S. Atlantic and Gulf coasts, the Arctic Ocean coast, and the coasts of the North Sea, particularly the Netherlands. The Outer Banks of North Carolina are probably the best-known barrier island chains. These environments are extremely vulnerable to increased storm intensities and sea level rises. An analytical model for predicting the impact of storms on barrier islands was recently developed in the Netherlands [56], and the predictions for the case of the impact of Hurricane Sandy on the US Atlantic compared well to the Delft 3D predictions but poorly to the observed outcomes. It was concluded that anthropogenically developed coasts do not behave as models predict. Landward transgressions of barrier islands involve more than wave and storm surge breaching. Physical and morphologic factors interact with numerous ecological factors to control barrier island stability [57]. Recent analyses of interannual sea level fluctuations caused by variability in the AMOC and Gulf Stream [45] contribute to episodic barrier island transgressions along the U.S. Atlantic coast.

Numerical Modeling of coastal morphodynamic changes is essential to informed planning for the future. Fortunately, there are numerous relatively sophisticated community models available. Some of these are briefly described by [58]. For long range climate change planning, a decadal-scale model of long-term coastal evolution that assimilates data from routine monitoring has been developed by [59]. It is very important to sustain monitoring programs in such a way that the data collected is accessible and thus used to test models in different coastal settings. Here, the application of technologies to use satellite imagery has dramatically increased the potential to repeatedly measure shoreline change at a very high resolution [55]. The Community Surface Dynamics Modeling System (CSDMS), maintained at the University of Colorado, Boulder (https://csdms.colorado.edu/wiki/Coastal_models) (accessed on 2 September 2023), is an accessible source for a total of 94 open-source numerical models for predicting coastal processes, including erosion, accretion, and sediment transport. Predicting the future responses of shores and coastal lands to climate change and rising seas will require the coupling of morphodynamic, ecological, physical, engineering, and socioeconomic models along with observational time series of morphological behavior.

5. Continental Shelf Processes

Continental shelves are the undersea foundations of coasts and are sources and sinks of much or all the sediments that are moved shoreward or seaward by energetic events to bring about coastal change [60]. The widths and configurations of the shelves also condition the forces that ultimately reach the shores to bring about morphodynamic changes, including tide range and the strength of tidal currents. There is little doubt that continental shelf width and slope play important roles in amplifying or attenuating the harmful impacts of storm surges and high waves, as explained in the subsection on coastal inundation. The increasing size and intensity of tropical cyclones means that wave agitation of shelf sediment will penetrate to greater depths. Analyses of CO_2 partial pressures in the waters of several continental shelves suggest that shelves may increasingly be serving as beneficial carbon sinks [61].

Shelves are the preferred habitat for most marine organisms, and recent research [56] shows that the current and future warming of shelf waters is already causing many species to shift poleward and into deeper water. Increased acidity in ocean and shelf waters has the potential to decrease the productivity of organisms that are carbonate dependent. The effect will be a decline in rates of carbonate sediment production from various sources on tropical and temperate climate continental shelves where there exist “carbonate factories” [61,62], While this is not directly a morphodynamic change, changes in the regional ecology of shelves can alter the roughness of the shelf bottom boundary layer and affect the transport of shelf sediments. The continental shelf fronting the Gulf of Mexico coast, including the coasts of Louisiana and West Florida, is exceptionally wide and gently sloping, and while this dissipates much wave energy, it also significantly amplifies storm surge, as noted earlier [42,63]. Recent numerical model projections for the effects of climate change on the West Florida shelf [64] suggest that warming combined with increased freshwater runoff is likely to increase stratification and limit upwelling.

An important connection exists between the shoreline erosion and accretion patterns discussed in the foregoing subsection and continental shelf configuration, composition, and process regimes. The link between the inner shelf or shoreface and coastal barrier stability and change was discussed in depth in [43]. For many years, coastal geologists and engineers accepted the classical “Bruun Rule”, whereby rises in sea level were assumed to be accompanied by the maintenance of a simple profile of equilibrium via upward and shoreward translation of the shore and a concave upward inner shelf profile [3,43]. However, that model, which was originally proposed by Per Bruun of the U.S. Army Corps of Engineers in 1954, involved overly simplifying assumptions that neglected morphodynamic feedback, sediment supply, and the increases in storm intensity, wave energy, and storm surges that are currently taking place. On sandy coasts such as that of Southeastern Australia, the continental shelf is both the source and the sink for the barrier sands. As explained in the previous subsection, multiple studies of shoreline behavior in Southeast Australia [52,53] and elsewhere [55] suggest that despite rising sea levels and increasing wave energy, there is no compelling evidence of sandy shores undergoing a net recession. Following the arguments presented by [43], it may be reasonably hypothesized that the more energetic waves are effectively transporting sands shoreward from mid- and outer shelf deposits. For this hypothesis to hold, however, there must be a relative abundance of sand on the mid- and outer continental shelves. Sand-deficient and muddy shelves would be expected to allow shoreline recession, as is commonly observed [63,65]. It must be remembered that moving large quantities of sand from the mid-shelf to the shore requires time. Hence, as emphasized by [43], lag times separating changes in wave climate from observed shoreline responses can be substantial. More field research must focus on the interconnections of climate change and continental shelf morphodynamic processes. As outlined in [65], research programs involving repeated mapping of the shoreface realms fronting coastal compartments that are subject to change are needed.

6. Low Elevation Coastal Zones (LECZ)

There is a broad consensus that, because of rising sea levels, Low Elevation Coastal Zones (LECZ) worldwide are vulnerable now and will be much more vulnerable in future decades [42,63,66]. The most recent study of impending LECZ damage from climate change [66] addresses the impacts on urban atoll communities, Arctic coastal settlements, agricultural deltaic environments, and resource-rich coastal cities. Various adaptation strategies will be required to mitigate harmful impacts. The most prominent morphodynamic responses to climate change in LECZ are the submergence of wetlands, the widening of estuaries and intertidal river courses, and reductions in the areas of habitable coastal land surfaces.

A recent analysis of the socioeconomic resilience of LECZ communities [67] employed fine-resolution spatial demographic methods to analyze the vulnerabilities of marginalized residents of US LECZ. The results of their study showed that from 1990 to 2020, the populations of US LECZ grew from 22 million to 31 million people, and that a disproportionate number of these residents are marginalized, low-income, and vulnerable Black, Hispanic, and elderly people. The finding that, of the nearly one-third of the US population living in coastal counties, nearly ten percent is at risk from coastal flooding by severe storms and sea level rise highlights the need for improved planning and adaptation measures.

The rates of sea level rise in coastal Virginia and the Chesapeake Bay significantly exceed the global rate, and interannual variations in sea level related to the weakening of the AMOC add to the annual rates. Like other LECZ, the population of this region is growing, and the number of people who become cut off from traveling to and from work by episodically flooded roads is increasing. High-resolution land use and LIDAR data were used by [68] to examine the increasing inaccessibility of roads throughout the affected region. It was concluded that road inaccessibility impacts property values and emergency response times, but that redundant road networks can increase resilience in the near term. Road elevation or construction may be regarded as anthropogenic morphodynamics.

7. Wetlands

Marshes, swamps, and tidal flats constitute a large fraction of the subaerial land surfaces on low-energy and relatively undeveloped coasts. A recent global analysis of these habitats [69] suggests that global warming more than 1.5 °C could lead to widespread declines in wetlands worldwide. Salt marshes, tidal creek networks, tidal flats, and shallow bays in middle and high latitudes, and mangrove forests in tropical and subtropical realms, are the common wetland environments. The classic view of the stability of salt marsh ecosystems is that equilibrium with gradual rises in relative sea level is attained when marsh grasses such as *Spartina alterniflora* increase productivity in pace with sea level rise and increase the trapping of inorganic sediments to raise the mash surface at the rate at which sea level is rising [41,70,71]. A recent study of global wetlands [72] concludes that rising sea levels could bring about the demise of 20% to 90% of the world's wetlands, but that the local rates of loss will depend heavily on whether there is adequate accommodation space to allow for landward migration. Sediment supply is also a critical factor in the resilience of marshes to rising sea levels. Some numerical models that consider accelerated rates of sea level rise accompanied by declining sediment supply by estuaries [73] conclude that marsh disequilibrium can cause marshes to be replaced by mudflats when sea level rises exceed some locally variable critical rate. A comprehensive analysis of measurements of tidal marsh accretion from different regions of the world with contrasting Holocene geologic histories identified the various constraints on the adjustment of tidal marshes to accelerating SLR [74]. This work was able to distinguish patterns of accretion linked to different rates of SLR and how the subsidence of substrates involves a nonlinear increase with accretion.

An assessment of tidal marsh resilience using the San Francisco estuary as a case study [71] identified the three primary metrics of tidal marsh resilience over time as being: (1) the time until sea level rise completely drowns the marsh; (2) the time until sea level reaches a tipping point beyond which marsh degradation will begin; and (3) the probability of a major shift in the process regime to a new and unstable state. The Coastal Wetland Equilibrium Model [41] was used to predict expected future marsh developments under different sea level rise scenarios. In addition to sediment supply and marsh vegetation, upland habitat was found in [73] to also play an important role in tidal marsh resilience by determining the extent of accommodation space through marsh migration. Future contributions focused on the details of observed and predicted tipping points for marsh degradation versus equilibrium are needed for contrasting marsh environments.

Mangroves on tropical and subtropical coasts provide important and highly effective protection against coastal erosion [75–78]. Mangrove intertidal ecosystems dissipate high waves, storm surges, and tsunamis [77]. Applications of the Delft3D model to a mangrove forest in New Zealand [77] indicated that the distribution of mangroves and patterns of associated channeling may be more important than the density of roots in attenuating waves and surges. That study also suggested that for mangroves to be effective in protecting coasts, they must also reduce the landward flow of water in addition to dissipating waves. The largest mangrove forest in the world is the Sundarbans of Bangladesh and India in the Ganges-Brahmaputra Delta [76,78]. Rising temperatures, sea level, and salinity, along with land subsidence, are causing landward shore transgression and significant losses to the Sundarbans mangrove forest [78]. Studies of mangrove ecosystems in a variety of geomorphic settings have shown how such losses can be attributed to shifts in the location of sediment sources, allowing the destruction of fringing wetlands due to wave erosion. The likely impacts of sea level rise on the Indo-Pacific mangrove ecosystem and the communities that depend on them are assessed in [79].

8. Estuaries, Bays, and Tidal Waterways

Rising seas, storm surges, dams on rivers, and reductions in sediment supply to coasts are altering the shapes and widths of estuaries, bays, and coastal waterways, including lagoons and tidal creeks. Several recent studies have documented changes that have taken place in recent years and are predicted by models to occur in the future. From a morphodynamic perspective, a key factor in understanding future change is the inherited history of estuarine shore morphologies. Coasts experiencing on-going relative SLR in the late Holocene provide a different setting to those where the shores of estuaries and bays reflect 6,000 or more years of relative sea level stability. During that time, estuary shores have adjusted to biophysical processes linked to inputs from both sea and land in ways that reflect those histories. Estuarine morphology influences tidal propagation and amplitude and the ways in which estuaries respond to deepening by sea level rise [80]. Vertical accretion in some very high-tide-range estuaries has seen the replacement of ecosystems because of changes in the frequency of tidal inundation [80]. However, permanent openings or deep dredging of entrances to estuaries and bays have often created circumstances for SLR and other climate change forces to adversely impact natural conditions. Work as long ago as the 1950s in Gippsland Lakes, Australia, demonstrated how entrance dredging has led to increased tidal range and saline waters destroying fringing reed marshes.

A study of Mobile Bay (Alabama) [81] examined the roles of interacting dredging, sea level rises, and wetlands inundation in affecting the navigability and sedimentation in the bay and its access channels and port facilities. Climate change is also causing the risk of riverine flooding in estuaries to increase [82]. A study of estuaries from 39 world-wide sites [83] concludes that rising sea levels not only alter the sizes and shapes of tidal estuaries but also alter the tide range, particularly at the estuaries' upper reaches. Similar results on the modification of the estuarine tidal range by rising sea levels were reported by [84,85]. For natural, unmodified estuaries, rising seas would tend not only to deepen the estuaries but also to widen them by flooding the surrounding wetlands and land surfaces. Increasing the size of estuaries can reduce the tidal range. However, model results for Chesapeake and Delaware Bays suggest that if engineering works such as levees or sea walls constrain the width, tides can be amplified and increase the flooding threat upstream [86].

Erosion or transgression of bars or barrier islands impounding lagoons can transition lagoons into shallow embayments or open coasts. A recent study of Cigu Lagoon in Taiwan [87] found that the size and environmental resilience of the lagoon are being reduced by the transgression and erosion of the impounding bar system, and this is having negative impacts on the local economy and quality of life of the residents. An assessment of climate change impacts on numerous estuarine systems in the Australian state of New South Wales [88] identified four distinct types or contexts of estuaries, each of which possesses different vulnerabilities and necessitates different management strategies. Many of these estuaries have been degraded by human activity and are seriously threatened by climate change [89]. The four estuarine contexts identified by [88] are: (1) intermittently closed and open lakes and lagoons; (2) coastal lakes; (3) deltaic floodplains; and (4) drowned river valleys. Warming water, rising sea levels, acidifying waters, and changing salinities are adding to the effects of population growth and increased development on the estuaries.

9. Deltaic Coasts

Worldwide, somewhere between 500 million and 600 million people live on or near river deltas [90,91]. For this reason, the interconnections among human-induced processes such as climate change, damming of rivers, land development, and delta morphodynamics are many and complex. These interactions are detailed in a recently edited volume [90] and in an internationally authored review article [91]. Many deltas support megacities with populations of over 10 million people [92]; there are more than 130 million inhabitants of the Ganges-Brahmaputra delta [78]. In contrast, the Mississippi Delta has a little more than 2 million inhabitants. Globally, 17 deltas are occupied by at least a million or more people [93]. Worldwide, 89 deltas exceed 1000 km^2 in total area [91].

Land subsidence, sea level rise, severance of sediment supply by dams, and the increasing severity of storms are causing accelerating land losses in most deltas [93]. The rates of Mississippi Delta subsidence are up to 18 mm/yr [93]. This subsidence, along with projected rates of global sea level rise of between 8 mm/yr and 16 mm/yr, means that the total relative rate of sea level rise in coastal Louisiana will conceivably be between 26 mm/yr and 34 mm/yr. As pointed out in Section 3, recent studies [39,94] have concluded that a sea level rise tipping point for many deltaic and coastal wetland surfaces to be replaced by open water is around 5 mm/yr. The Louisiana Coastal Protection and Reclamation Authority [95] projects that by 2050, without reclamation, most of the wetlands will have been replaced by open water. NASAs Jet Propulsion Laboratory recently launched its "Delta-X" initiative to collect and analyze high-resolution airborne data focused on delta vulnerability and resilience.

Submergence is prevailing in most other deltas, though at varying rates. From our understanding of delta geology, it is recognized that, by avulsion, many deltas switch their centers of discharge, allowing rapid delta-front growth in some places and leaving other abandoned sections to decay because of subsidence and wave erosion. This can occur without a significant change in relative sea level, as in the Purari in PNG. However, in parts of China's Pearl River Delta, submergence rates are up to 15 mm/yr, and with a projected maximum sea level rise of an additional 1.3 m by 2100, much of the existing land surface could be replaced by open water [96]. Serious subsidence of as much as 40 mm/yr is taking place in the Venice lagoon [93]. A recent study of the Omo River Delta in Kenya [10] showed that reduced sediment discharge by dams is causing land loss and channel deepening. The Huang He (Yellow River) delta is currently being submerged at a rate of 250 mm (10 inches) per year because dams and the extraction of water for agriculture have completely halted the delivery of land-building sediment to the sea. The Huang He Delta no longer has any subaerial surface expression. The gradients of most deltaic surfaces are extremely gentle, and this means that comparatively small vertical rises in coastal waters can result in large horizontal excursions by inundation from the sea.

While the progressive rise in global mean sea level poses a long-term problem for all deltas, the most pronounced morphodynamic consequences are caused by episodic extreme events such as storm-induced surges and destructive waves, extreme river floods, and, in some cases, human activity [97]. The morphodynamic responses of river deltas to varying water depths in the receiving basins (seas or lakes) were examined by tank experiments and explained in terms of a "Gradient Index Model" [98]. Not unexpectedly, it was concluded that delta progradation is retarded when the basins are deep but enhanced when the basins are shallow. Most large river deltas are fronted by wide, low-gradient continental shelves. Even though shallow shelves favor delta progradation and aggradation, they also amplify destructive storm surges that can travel upstream, undergoing further amplification within tidal funnel-shaped estuaries. Much more research on the complex, multi-faceted morphodynamic processes that operate in deltas and change with the climate is needed.

10. Arctic Coasts

Rapid warming of the Arctic Ocean and sea level rise are already impacting the morphodynamics of low-elevation Arctic coasts, the unique Arctic ecosystems, and Native subsistence, health, and culture [66]. These assets are dependent on a frozen ocean and frozen permafrost on land. Recent studies indicate that since 1979, near-surface air temperatures in the Arctic have risen four times faster than temperatures elsewhere on the earth's surface [99]. Earlier estimates that Arctic temperatures were rising 2–3 times faster than elsewhere were referred to as the Arctic Amplification [100]. The melting of sea ice in the Beaufort and Chukchi Seas is allowing larger and warmer wind-generated waves to attack the low-lying shores, causing extensive thermal erosion of the permafrost-cemented coast and the lands behind [101,102]. About 25% of the world's barrier islands are on the low-elevation Arctic coast and are being rapidly eroded and reconfigured [65,102,103]. The rate of barrier island recession on the Beaufort Sea coast is three to four times faster than in other regions of the continental United States. The significant reconfiguration of Arctic barrier islands has already led to the erosion and relocation of a rural Alaskan community [104]. The melting of the permafrost underlying the wide, tundra-covered coastal plain of the Arctic North Slope is causing collapse of the land surface and releases of methane gas [105]. Glaciers melting inland from the coast are causing wintertime river flows to rise [106,107].

The most serious and damaging socioeconomic impacts of the unfolding changes are felt by indigenous Arctic people [108]. Native inhabitants of Arctic Alaska have a symbiotic relationship with their natural realm and rely on hunting, fishing, trapping, reindeer herding, and gathering for sustenance. The disappearance of protective barrier islands is causing the loss of critical wildlife habitat. There are also direct impacts on housing and village infrastructure. Melting permafrost causes a loss of support for structures built on the tundra surface, and shore retreat is displacing villages. Some engineering solutions to permafrost thawing utilizing steel pilings are being explored [109]; however, this solution is unaffordable for most indigenous people.

11. Coral Reefs and Reef Islands

Coral reefs have traditionally served as the natural protectors of tropical coasts, and they have proved to be highly resilient. As with any future projections of potential change to the morphologies of coastal landforms in the new climate era, the inherited nature of landforms and their evolution should form part of the analysis. A diversity of Holocene reef studies in different tropical oceans have indicated varying reef growth strategies in relation to sea level rise: some kept up; others could not as the rate of SLR declined, stabilized, or accelerated [110,111]. Further understanding of the geological and geographical variability of reef systems will assist in deciphering how coral reefs will respond to future SLR. Several recent studies based on morphodynamic principles and observations have challenged the assumption that increased flooding due to SLR will automatically render reef islands uninhabitable within decades [110,112]. For instance, results have shown that the magnitude of island change from a range of locations over the past 50 years is not unprecedented compared with paleo-dynamic evidence that has defined large-scale changes in island dimension, shape, and beach levels since island formation c. 1500 years ago. The authors argue convincingly that their results highlight the value of a multi-temporal methodological approach to gain a deeper understanding of the dynamic trajectories of reef islands to assist in the development of adaptation strategies for the people of these islands.

While coral reefs and reef islands may tolerate rising sea levels, rising sea temperatures are proving to be more problematic. Rising temperatures are causing the bleaching of coral's symbiotic microalgae, the source of coral nourishment, and this eventually leads to coral death. For some island nations such as the Maldives, narrow, fringing reefs offer the only protection from rising seas. Elsewhere, offshore reefs are highly effective in dissipating storm waves, thereby sheltering the shores that lie behind [113], but the degradation of reefs allows more energetic waves to reach the hinterland shores and communities [114]. Today, rising sea surface temperatures are having devastating impacts on coral reefs worldwide [115,116]. Australia's Great Barrier Reef (GBR) is probably the most prominent example [116,117]. In the month of July 2023, sea temperatures in the Florida Keys reached 38.4 °C, causing extensive coral bleaching and the death of a local reef (Sombrero Key). In 2016, roughly 20% of the GBR experienced bleaching when the temperature reached 29.1 °C [116]. With ocean temperatures around GBR expected to rise by an additional 1–2 °C by 2030, new management approaches to conserve this unique marine ecosystem have been launched in a program involving a partnership between marine scientists and indigenous people [118]. Strategies for restoring reefs include raising new stocks of heat-tolerant coral in aquaculture facilities and transplanting those stocks onto reefs. Similar coral restoration programs are underway elsewhere, including Florida [119].

12. Built and Natural Protective Infrastructure

Coastal landscapes are increasingly anthropogenic as the necessity for protection against rising seas, storms, and floods continues to grow along with increasing urbanization [120,121]. Traditionally, hard-engineered structures such as seawalls, levees, and dikes have been relied on, and the U.S. Army Corps of Engineers has led the development of engineered protections in the US. However, the Netherlands has, for many decades, led the world in keeping the sea out of their cities and communities. Following the catastrophe of Hurricane Katrina, the U.S. Army Corps of Engineers completed a $14.5B flood protection system surrounding New Orleans intended to withstand a 100-year flood event. This system consists of levees, a storm surge barrier, and high-volume pumps [122]. This protection is limited to the city of New Orleans. The rest of coastal Louisiana is losing land and wetlands at a phenomenal rate, and addressing this problem is the focus of extensive and highly complex coastal restoration programs [95,123].

Coastal protection agencies are increasingly turning to nature-based alternatives to engineered structures [124–128]. Wetland restoration, planting of mangrove forests, diversion of sediment-bearing river channels, nurturing coral reefs, and abandoning "grey infrastructure" (which often tends to work against natural infrastructure)—while breakwaters and seawalls often tend to exacerbate rather than stop the offshore loss of beach sand, an intermediate approach, termed "living shorelines," may prove useful in offering resilience to adverse impacts of hard structures. It involves a combination of intermittently spaced minimalist hard structures and natural wetlands, or mangroves [128]. Of course, one of the best "nature-based" approaches is to simply allow the natural erosion/accretion cycles to proceed without structural impedance and not permit construction within a certain distance from the active zone. The iconic coastal geologist and environmentalist, Orin Pilkey, has spent many decades advocating retreat as the best alternative to harmful engineering practices. However, in many cases, especially on densely populated urban coasts, the relocation of entire communities is simply not feasible [42,63,69]. Nature-based adaptations can also deliver ecological, recreational, and other services. However, as pointed out in [42], "for these benefits to fully manifest, we must first understand how design and decision optima are influenced by consideration of diverse, uncertain ecosystem services." Unfortunately, in an increasing number of cases, managed retreat is the only feasible solution, even though it is always the last resort.

Coastal management challenges in areas where there are conflicts over future use have been outlined in a recent paper, including legal and social issues that arise, especially in the management of contested beach areas [129]. An emerging, but less well acknowledged, strategy involves deploying the approaches long used by indigenous people, including Native Americans and Indigenous Australians [130,131]. The Indigenous Australians have occupied and adapted to their natural environment for over 60,000 years, and many of the coastal marine ecosystems are sacred to them [131]. Notably, the concept of private "ownership" of natural environments does not exist within ancient indigenous cultures.

13. Conclusions and Prognosis for Future Advances

The primary aim of this brief review has been to point out some of the more recent advances in understanding existing and potential future linkages between climate change and coastal morphodynamic subsystems. This review has not been comprehensive, and the list of references cited is far from exhaustive. This is an introduction to new and innovative understandings of the changes that are already underway or likely to emerge in the future. From the works referenced in the foregoing review, it is hopefully clear that numerous processes are changing in the ways that they interact with each other and with coastal landforms to bring about morphodynamic change. There is rarely a single factor that accounts for a particular change. Of course, the primary driver behind global climate change is the increasing temperature of the atmosphere, ocean, and solid earth. And compelling evidence shows that this warming is attributable to the fact that the atmosphere is now able to capture and hold more heat because of increases in the atmospheric concentrations of carbon dioxide and methane. But, from the perspective of coastal morphodynamics, the most consequential and damaging impacts arise from increasing ocean temperatures. Roughly 93% of the heat from global warming goes into the sea, where it is stored. Figure 2 shows a NASA map of sea surface temperature anomalies on 21 August 2023, near the end of the hottest northern hemisphere summer on record. The areas in dark red are more than 3 °C above average. Record-high temperatures persisted for four consecutive months. A warming ocean is the major cause of several important morphodynamic impacts. These include global rises in sea level; the increasing size and intensity of the tropical storms that bring destructive waves and storm surges; the accelerating melting of sea ice; the deaths of coral reefs; and the weakening of the Atlantic Meridional Overturning Circulation (AMOC). Other impacts include reductions in dissolved oxygen, increases in harmful algal blooms and pathogens in estuaries, and lingering flood waters. Changes in atmospheric circulation and storm genesis are increasing the occurrence of flash flooding caused by intense and torrential rainstorms.

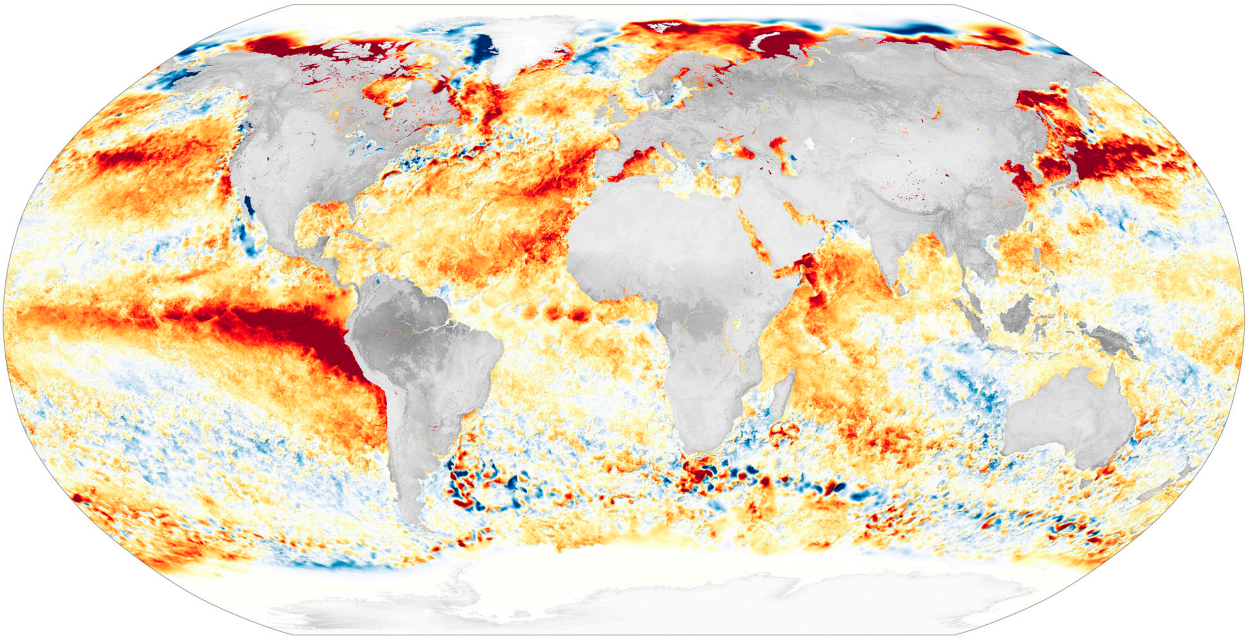

Figure 2. Global sea surface temperature anomalies on 21 August 2023. Dark reds indicate temperatures more than 3 °C above average. Orange areas are 1–2 °C above average. Source: NASA Earth Observatory, based on data from the Multiscale Ultrahigh Resolution Sea Surface Temperature (MUR SST) project. Record high temperatures prevailed for four consecutive months.

Fortunately, new innovative approaches to coastal protection and management, including nature-based strategies, offer some promise for the mitigation of coastal degradation. A comprehensive inventory of modeling strategies appropriate to modeling the effects of climate change on coastal morphology, especially coastal recession, is offered by [33]. The historical background to coastal modeling approaches described in that work begins with the very simplistic "Bruun Rule" (mentioned in Section 5), which has been modified several times over the past 60 years to address first-order questions about directions of potential change. The current state-of-the-art approaches discussed in [33] include behavior-based models such as Genesis, process-based models such as DELFT3-D developed by Delft University in the Netherlands, and several reduced complexity models, some of which are proprietary. However, as pointed out by [132], more advanced complex systems modeling results are urgently needed to anticipate future coastal threats, and prolonged time series of observed data are needed to validate and refine predictive models.

Innovative engineering solutions are needed to adapt to changes in coastal landscapes and environmental risks. Model improvements are also vital to the ability of coastal managers to better anticipate when a critical tipping point may be approaching. We have highlighted some recent advances in identifying critical tipping points and cascading physical, ecological, socioeconomic, and multi-faceted complex systems. For the most part, the current understandings are incipient building blocks for more advances yet to come. Further contributions based on observational or numerically modeled research, as well as review papers, regional case studies, and global projections, are still needed. Finally, as pointed out in [133], p. 347, "adaptive regional strategies are required to reduce the risk of harm to valued coastal assets and to overcome the numerous barriers to long-term planning at different spatial scales". In addition, such strategies must be incorporated into a well-understood public policy and legal framework that include climate change adaptation policies that recognize the need for action at certain thresholds or trigger points.

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References

1. Wright, L.D.; Thom, B.G. Coastal depositional landforms: A morphodynamic approach. *Prog. Phys. Geogr.* **1977**, *1*, 412–459. [CrossRef]
2. Cowell, P.J.; Thom, B.G. Morphodynamics of coastal evolution. In *Coastal Evolution: Late Quaternary Shoreline Morphodynamics*; Carter, R.W.G., Woodroffe, C.D., Eds.; Cambridge University Press: Cambridge, UK, 1994; pp. 33–86.
3. Wright, L.D. *Morphodynamics of Inner Continental Shelves*; CRC Press: Boca Raton, FL, USA, 1995; p. 241.
4. Woodroffe, C.D. *Coasts—Form and Processes*; Cambridge University Press: Cambridge, UK, 2002.
5. Sutherland, J. Coastal Morphodynamics and Society. 2008. Available online: http://www.coastalwiki.org/wiki/Coastal_morphodynamics_and_society (accessed on 30 July 2023).
6. Barman, N.K.; Chatterjee, S.; Paul, A.K. *Coastal Morphodynamics: Integrated Spatial Modeling on the Deltaic Balasore Coast, India*; Springer Briefs in Geography; Springer: Berlin/Heidelberg, Germany, 2016; ISBN 978-3-319-33574-2.
7. Friedrichs, C.T. Tidal Flat Morphodynamics: A Synthesis. *Treatise Estuar. Coast. Sci.* **2011**, *3*, 137–170.
8. Wright, L.D.; Syvitski, J.; Nichols, C.R.; Zinnert, J. Coastal Morphodynamics and Ecosystem Dynamics. In *Tomorrow's Coasts: Complex and Impermanent*; Wright, L.D., Nichols, C.R., Eds.; Coastal Research Library Series; Springer: Cham, Switzerland, 2019; pp. 69–84.
9. Jackson, D.W.T.; Short, A.D. *Sandy Beach Morphodynamics*; Elsevier: Amsterdam, The Netherlands, 2020; p. 817.
10. Zen, S.; Perona, P.; Medina-Lopez, E. River delta eco-morphodynamics under changing scenarios: The case of Lake Turkana, Kenya. *Geomorphology* **2023**, *428*, 108640. [CrossRef]
11. Barnard, P.L.; Dugan, J.E.; Page, H.M.; Wood, N.; Hart, J.; Cayan, D.; Erikson, L.; Hubbard, D.; Myers, M.; Melack, J.; et al. Multiple climate change-driven tipping points for coastal systems. *Sci. Rep.* **2021**, *11*, 15560. [CrossRef]
12. Wuebbles, D.J.; Fahey, D.W.; Hibbard, K.A.; DeAngelo, B.; Doherty, S.; Hayhoe, K.; Horton, R.; Kossin, J.P.; Taylor, P.C.; Waple, A.M.; et al. *Executive Summary of the Climate Science Special Report: Fourth National Climate Assessment, Volume I*; Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., Maycock, T.K., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2017; p. 26.
13. U.S. Global Change Research Program. *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2023*; U.S. Global Change Research Program: Washington, DC, USA, 2023.
14. Arias, P.A.; Bellouin, N.; Coppola, E.; Jones, R.G.; Krinner, G.; Marotzke, J.; Naik, V.; Palmer, M.D.; Plattner, G.; Joeri Rogelj, J.; et al. Technical Summary. In *Climate Change: The Physical Science Basis. Contribution of Working Group 14 I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*; Cambridge University Press: Cambridge, UK, 2021.
15. Bondre, N.; Gaffney, O. (Eds.) *IGBP Annual Report 2014/2015*; IGBP Secretariat, The Royal Swedish Academy of Sciences: Stockholm, Sweden, 2015.
16. Janssen, M. Use of complex adaptive systems for modeling global change. *Ecosystems* **1998**, *1*, 457–463. [CrossRef]
17. Nicolis, G.; Prigogine, I. *Exploring Complexity*; Freeman &, Co.: New York, NY, USA, 1989; p. 313.
18. Hendrickx, G.G.; Antolínez, J.A.A.; Herman, P.M.J. Predicting the response of complex systems for coastal management. *Coast. Eng.* **2023**, *182*, 104289. [CrossRef]
19. Sweet, W.V.; Hamlington, B.D.; Kopp, R.E.; Weaver, C.P.; Barnard, P.L.; Bekaert, D.; Brooks, W.; Craghan, M.; Dusek, G.; Frederikse, T.; et al. *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*; NOAA Technical Report NOS 01; National Oceanic and Atmospheric Administration, National Ocean Service: Silver Spring, MD, USA, 2022; p. 111. Available online: https://oceanservice.noaa.gov/hazards/sealevelrise/noaa--nos-techrpt01-global-regional-SLR-scenarios-US.pdf (accessed on 30 July 2023).
20. Ezer, T.; Atkinson, L.P. Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream.; the North Atlantic Oscillations. *Earth's Future* **2014**, *2*, 362–382. [CrossRef]
21. Ditlevsen, P.; Ditlevsen, S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat. Commun.* **2023**, *14*, 4254. [CrossRef]
22. Ranasinghe, R.; Callaghan, D.P.; Li, F.; Wainwright, D.J.; Duong, T.M. Assessing coastline recession for adaptation planning: Sea level rise versus storm erosion. *Sci. Rep.* **2023**, *13*, 8286. [CrossRef]

23. Lukasiewicz, A.; O'Donnell, T. *Complex Disasters: Compounding, Cascading, and Protracted*; Lukasiewicz, A., O'Donnell, T., Eds.; Palgrave Macmillan: Singapore, 2022.
24. Zscheischler, J.; Westra, S.; van den Hurk, B.J.J.M.; Seneviratne, S.I.; Ward, P.J.; Pitman, A.; AghaKouchak, A.; Bresch, D.N.; Leonard, M.; Wahl, T.; et al. Future climate risk from compound events. *Nat. Clim. Chang.* **2018**, *8*, 469–477. [CrossRef]
25. Shen, Y.; Morsy, M.M.; Huxley, C.; Tahvildari, N.; Goodall, J.L. Flood risk assessment and increased resilience for coastal urban watersheds under the combined impact of storm tide and heavy rainfall. *J. Hydrol.* **2019**, *579*, 124159. [CrossRef]
26. Wahl, T.; Jain, S.; Bender, J.; Meyers, S.D.; Luther, M.E. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nat. Clim. Chang.* **2015**, *5*, 1093–1097. [CrossRef]
27. Chen, W.-B.; Liu, W.-C. Modeling flood inundation induced by river flow and storm surges over a river basin. *Water* **2014**, *6*, 3182–3199. [CrossRef]
28. Balaguru, K.; Xu, W.; Chang, C.C.; Leung, L.R.; Judi, D.R.; Hagos, S.M.; Wehner, M.F.; Kossin, J.P.; Ting, M. Increased U.S. coastal hurricane risk under climate change. *Sci. Adv.* **2023**, *9*, eadf0259. [CrossRef] [PubMed]
29. Luettich, R.A., Jr.; Wright, L.D.; Signell, R.; Friedrichs, C.; Friedrichs, M.; Harding, J.; Fennel, K.; Howlett, E.; Graves, S.; Smith, E.; et al. Introduction to special section on the U.S. IOOS Coastal and Ocean Modeling Testbed. *J. Geophys. Res. Ocean.* **2013**, *118*, 6319–6328. [CrossRef]
30. NOAA's Updated P-Surge Model. Available online: https://slosh.nws.noaa.gov/psurge/index.php?S=Psurgetest22023&Adv (accessed on 10 August 2023).
31. Wright, L.D.; Nichols, C.R. (Eds.) . *Tomorrow's Coasts: Complex and Impermanent*; Coastal Research Library Series; Springer: Cham, Switzerland, 2019; p. 374.
32. Nichols, C.R.; Wright, L.D. The evolution and outcomes of a collaborative testbed for predicting coastal threats. *J. Mar. Sci. Eng.* **2020**, *8*, 612. [CrossRef]
33. Luettich, R.A., Jr.; Wright, L.D.; Nichols, C.R.; Baltes, R.; Friedrichs, M.A.M.; Kurapov, A.; van der Westhuysen, A.; Fennel, K.; Howlett, E. A test bed for coastal and ocean modeling. *Eos* **2017**, *98*. [CrossRef]
34. Luettich, R.A.; Westerink, J.J.; Scheffner, N.W. *ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries*; Report 1, Theory and Methodology of ADCIRC-2DD1 and ADCIRC-3DL; Coastal Engineering Research Center: Miami, FL, USA, 1992; 48p.
35. Camelo, J.; Mayo, T.L.; Gutmann, E.D. Projected Climate Change Impacts on Hurricane Storm Surge Inundation in the Coastal United States. *Front. Built Environ.* **2020**, *6*, 588049. [CrossRef]
36. Goodwin, I.; Ribó, M.; Mortlock, T. Coastal sediment compartments, wave climate and centennial-scale sediment budget. In *Sandy Beach Morphodynamics*; Derek, W.T., Jackson, A., Short, D., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 615–640. ISBN 9780081029275. Available online: https://www.sciencedirect.com/science/article/pii/B9780081029275000254 (accessed on 20 August 2023).
37. McKay, D.; Staal, A.; Abrams, J.; Winkelman, R.; Sakschewski, B.; Loriani, S.; Fetzer, I.; Cornell, S.; Rockstrom, J.; Lenton, T. Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science* **2022**, *377*, eabn7950. [CrossRef]
38. Lenton, T.M. Early warning of climate tipping points. *Nat. Clim. Chang.* **2011**, *1*, 201–210. [CrossRef]
39. Turner, R.E.; Kearney, M.S.; Parkinson, R.W. Sea-level rise tipping point of delta survival. *J. Coast. Res.* **2018**, *34*, 470–474. [CrossRef]
40. Wright, L.D.; Syvitski, J.; Nichols, C.R. Complex Intersections of Seas, Lands, Rivers, and People. In *Tomorrow's Coasts: Complex and Impermanent*; Wright, L.D., Nichols, C.R., Eds.; Coastal Research Library Series; Springer: Cham, Switzerland, 2019; pp. 59–68.
41. Morris, J.T.; Cahoon, D.R.; Callaway, J.C.; Craft, C.; Neubauer, S.C.; Weston, N.B. Marsh equilibrium theory: Implications for responses to rising sea level. In *Salt Marshes: Function, Dynamics, and Stresses*; FitzGerald, D.M., Hughes, Z.J., Eds.; Cambridge University Press: Cambridge, UK, 2021; pp. 157–177.
42. Allen, T.; Behr, J.; Bukvic, A.; Calder, R.S.D.; Caruson, K.; Connor, C.; D'Elia, C.; Dismukes, D.; Ersing, R.; Franklin, R.; et al. Anticipating and Adapting to the Future Impacts of Climate Change on the Health, Security and Welfare of Low Elevation Coastal Zone (LECZ) Communities in Southeastern USA. *J. Mar. Sci. Eng.* **2021**, *9*, 1196. [CrossRef]
43. Cowell, P.J.; Kinsela, M.A. Shoreface controls on barrier evolution and shoreline change. In *Barrier Dynamics, Response to Changing, Climate*; Moore, L.J., Murray, B.A., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2018. [CrossRef]
44. Zarillo, G.A. Inter-annual sea level change and transgression along a barrier Island coast. *Front. Environ. Sci.* **2023**, *11*, 1107458. [CrossRef]
45. Boers, N. Observation-based early warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Change* **2021**, *11*, 680–688. [CrossRef]
46. Hauer, M.E.; Fussell, E.; Mueller, V.; Burkett, M.; Call, M.; Abel, K.; McLeman, R.; Wrathall, D. Sea-level rise and human migration. *Nat. Rev. Earth Environ.* **2020**, *1*, 28–39. [CrossRef]
47. Reimann, L.; Jones, B.; Bieker, N.; Wolff, C.; Aerts, J.C.; Vafeidis, A.T. Exploring spatial feedbacks between adaptation policies and internal migration patterns due to sea-level rise. *Nat. Commun.* **2023**, *14*, 2630. [CrossRef] [PubMed]
48. Fruergaard, M.; Møller, I.; Johannessen, P.; Nielsen, L.H.; Andersen, T.J.; Nielsen, L.; Sander, L.; Pejrup, M. Stratigraphy, evolution, and controls of a Holocene transgressive-regressive barrier island under changing sea-level: Danish North Sea coast. *J. Sediment. Res.* **2015**, *85*, 820–844. [CrossRef]

49. Hein, C.J.; FitzGerald, D.M.; deMenezes, J.T.; Cleary, W.J.; Klein, A.; Albernaz, M. Coastal response to late-stage transgression and sea-level highstand. *GSA Bull.* **2014**, *26*, 615. [CrossRef]
50. Masselink, G.; Russell, P.; Rennie, A.; Brooks, S.; Spencer, T. Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK. *MCCIP Sci. Rev.* **2020**, 158–189. [CrossRef]
51. Shadrick, J.R.; Rood, D.H.; Hurst, M.D.; Piggotti, M.; Hebditch, B.; Seal, A.; Wlicken, K. Sea-level rise will likely accelerate rock coast cliff retreat rates. *Nat. Commun.* **2022**, *13*, 7005. [CrossRef]
52. Short, A.D. Australian beach systems: Are they at risk to climate change? *Ocean. Coast. Manag.* **2022**, *224*, 106180. [CrossRef]
53. McLean, R.; Thom, B.; Shen, J.; Oliver, T. 50 years of beach–foredune change on the southeastern coast of Australia: Bengello Beach, Moruya, NSW, 1972–2022. *Geomorphology* **2023**, *439*, 108850. [CrossRef]
54. Ghanavati, M.; Young, I.; Kirezci, E.; Ranasinghe, R.; Duong, T.; Arjen, P.; Luijendijk, A. An assessment of whether long-term global changes in waves and storm surges have impacted global coastlines. *Sci. Rep.* **2023**, *13*, 11549. [CrossRef] [PubMed]
55. Vos, K.; Harley, M.D.; Turner, I.L.; Splinter, K. Pacific shoreline erosion and accretion patterns controlled by El Niño/Southern Oscillation. *Nat. Geosci.* **2023**, *16*, 140–146. [CrossRef]
56. Nienhuis, J.H.; Heijkers, L.G.H.; Ruessink, G. Barrier breaching versus overwash depositon. Predicting The morphologic impact of Storms on coastal barriers. *J. Geophys. Res. Earth Surf.* **2021**, *126*, e2021JF006066. [CrossRef]
57. Zinnert, J.C.; Via, S.M.; Nettleton, B.P.; Tuley, P.A.; Moore, L.J.; Stallins, J.A. Connectivity in coastal systems: Barrier Island vegetation influences upland migration in a changing climate. *Glob. Chang. Biol.* **2019**, *25*, 2419–2430. [CrossRef]
58. Wright, L.D.; Syvitski, J.; Nichols, C.R. Coastal Complexity and Predictions of Change. In *Tomorrow's Coasts: Complex and Impermanent*; Wright, L.D., Nichols, C.R., Eds.; Coastal Research Library Series; Springer: Cham, Switzerland, 2019; pp. 3–23.
59. Vitousek, S.; Barnard, P.L.; Limber, P.; Erikson, L.; Cole, B. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *J. Geophys. Res. Earth Surf.* **2017**, *122*, 782–806. [CrossRef]
60. Wright, L.D. Recent advances in understanding continental shelf sediment transport. *Int. Assoc. Sedimentologists. Spec. Publ.* **2012**, *44*, 159–172.
61. Laruelle, G.; Cai, W.-J.; Hu, X.; Gruber, N.; Mackenzie, F.; Regnier, P. Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide. *Nat. Commun.* **2018**, *9*, 454. [CrossRef]
62. Kitchel, Z.J.; Conrad, H.M.; Selden, R.L.; Pinsky, M.L. The role of continental shelf bathymetry in shaping marine range shifts in the face of climate change. *Glob. Change Biol.* **2022**, *28*, 5185–5199. [CrossRef]
63. Wright, L.D.; Caruson, K.; D'Elia, C.; Draayer, J.; Nichols, C.R.; Weiss, R.; Zarillo, G. *Assessing and Planning for the Impacts of Storms, Flooding and Sea Level Rise on Vulnerable Gulf of Mexico Coastal Communities: A White Paper*; Global Oceans: Singapore; U.S. Gulf Coast: Biloxi, MS, USA, 2020; pp. 1–6.
64. Chérubin, L.M.; Burgman, R.J. Effects of climate change and water management on West Florida Shelf's dynamics. *Bull. Mar. Sci.* **2022**, *98*, 393–418. [CrossRef]
65. Kinsela, M.A.; Hanslow, D.J.; Carvalho, R.C.; Kinsela, M.; Hanslow, D.J.; Carvalho, R.C.; Linklater, M.; Ingleton, T.; Morris, B.; Allen, K.; et al. Mapping the Shoreface of Coastal Sediment Compartments to Improve Shoreline Change Forecasts in New South Wales, Australia. *Estuaries Coasts* **2022**, *45*, 1143–1169. [CrossRef]
66. Magnan, A.K.; Oppenheimer, M.; Garschagen, M.; Buchanan, M.; Duvat, V.; Forbes, D.; Ford, J.; Lambert, E.; Petzold, J.; Renaud, G.; et al. Sea level rise risks and societal adaptation benefits in low-lying coastal areas. *Sci. Rep.* **2022**, *12*, 10677. [CrossRef] [PubMed]
67. Tagtachian, D.; Balk, D. Uneven vulnerability: Characterizing population composition and change in the low elevation coastal zone in the United States with a climate justice lens, 1990–2020. *Front. Environ. Sci.* **2023**, *11*, 1111856. [CrossRef]
68. Mitchell, M.; Hendricks, J.; Schatt, D. Road network analyses elucidate hidden road flooding impacts under accelerating sea level rise. *Front. Environ. Sci.* **2023**, *11*, 1083282. [CrossRef]
69. Saintilan, N.; Horton, B.; Törnqvist, T.E.; Ashe, E.; Khan, N.; Schuerch, M.; Perry, C.; Kopp, R.; Garner, G.; Murray, N.; et al. Widespread retreat of coastal habitat is likely at warming levels above 1.5 °C. *Nature* **2023**, *621*, 112–119. [CrossRef]
70. Morris, J.T.; Sundareshwar, P.V.; Nietch, C.T.; Kjerfve, B.; Cahoon, D.R. Responses of coastal wetlands to rising sea level. *Ecology* **2002**, *83*, 2869–2877. [CrossRef]
71. Morris, J.T.; Drexler, J.Z.; Vaughn, L.J.; Robinson, A.H. An assessment of future tidal marsh resilience in the San Francisco Estuary through modeling and quantifiable metrics of sustainability. *Front. Environ. Sci.* **2022**, *10*, 1039143. [CrossRef]
72. Schuerch, M.; Spencer, T.; Temmerman, S.; Kirwan, M.L.; Wolff, C.; Lincke, D.; McOwen, C.J.; Pickering, M.D.; Reef, R.; Vafeidis, A.T.; et al. Future response of global coastal wetlands to sea-level rise. *Nature* **2018**, *561*, 231–234. [CrossRef]
73. Schile, L.M.; Callaway, J.C.; Morris, J.T.; Stralberg, D.; Parker, V.T.; Kelly, M. Modeling tidal marsh distribution with Sea-Level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. *PLoS ONE* **2014**, *9*, e88760. [CrossRef]
74. Saintilan, N.; Saintilan, N.; Kovalenko, K.E.; Guntenspergen, G.; Rogers, K.; Lynch, J.C.; Cahoon, D.R.; Lovelock, C.E.; Friess, D.A.; Ashe, E.; et al. Constraints on the adjustment of tidal marshes to accelerating sea level rise. *Science* **2022**, *377*, 523–527. [CrossRef] [PubMed]
75. Menéndez, P.; Losada, I.J.; Torres-Ortega, S.; Narayan, S.; Beck, M.W. The Global Flood Protection Benefits of Mangroves. *Sci. Rep.* **2020**, *10*, 4404. [CrossRef] [PubMed]

76. Ishtiaque, A.; Myint, S.W.; Wang, C. Examining the ecosystem health and sustainability of the world's largest mangrove forest using multi-temporal MODIS products. *Sci. Total Environ.* **2016**, *569–570*, 1241–1254. [CrossRef]
77. Montgomery, M.; Bryan, K.R.; Coco, G. The role of mangroves in coastal flood protection: The importance of channelization. *Cont. Shelf Res.* **2022**, *243*, 104762. [CrossRef]
78. Alam, E.; Momtaz, S.; Bhuiyan, H.U.; Baby, S.N. Climate change impacts on the coastal zones of Bangladesh: Perspectives on tropical cyclones, sea level rise, and social vulnerability. In *Bangladesh I: Climate Change Impacts, Mitigation and Adaptation in Developing Countries*; Islam, M., van Amstel, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 145–166. [CrossRef]
79. Lovelock, C.; Cahoon, D.; Friess, D.; Guntenspergen, G.R.; Krauss, K.W.; Reef, R.; Rogers, K.; Saunders, M.L.; Sidik, F.; Swales, A.; et al. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature* **2015**, *526*, 559–563. [CrossRef]
80. Kumbier, K.; Rogers, K.; Hughes, M.G.; Lal, K.K.; Mogensen, L.A.; Woodroffe, C.D. An Eco-Morphodynamic Modelling Approach to Estuarine Hydrodynamics & in Response to Sea-Level Rise. *Front. Mar. Sci.* **2022**, *9*, 860910. [CrossRef]
81. Munñoz, D.F.; Moftakhari, H.; Kumar, M.; Moradkhani, H. Compound Effects of Flood Drivers, Sea Level Rise, and Dredging Protocols on Vessel Navigability and Wetland Inundation Dynamics. *Front. Mar. Sci.* **2022**, *9*, 906376. [CrossRef]
82. Ghanbari, M.; Arabi, M.; Kao, S.-C.; Obeysekera, J.; Sweet, W. Climate change and changes in compound coastal-riverine flooding hazard along the U.S. coasts. *Earth's Future* **2021**, *9*, e2021EF002055. [CrossRef]
83. Leuven, J.R.F.W.; Pierik, H.J.; Vegt, M.v.d.; Bouma, T.J.; Kleinhans, M.G. Sea-level-rise-induced threats depend on the size of tide-influenced estuaries worldwide. *Nat. Clim. Chang.* **2019**, *9*, 986–992. [CrossRef]
84. Khojasteh, D.; Chen, S.; Felder, S.; Heimhuber, V.; Glamore, W. Estuarine tidal range dynamics under rising sea levels. *PLoS ONE* **2021**, *16*, e0257538. [CrossRef]
85. Reeve, D.E.; Karunarathna, H. On the prediction of long-term morphodynamic response of estuarine systems to sea level rise and human interference. *Cont. Shelf Res.* **2009**, *29*, 938–950. [CrossRef]
86. Lee, S.B.; Ming, L.; Zhang, F. Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *J. Geophys. Res. Ocean.* **2017**, *122*, 3917–3938. [CrossRef]
87. Phuah, T.L.-K.; Chang, Y.-C. Socioeconomic adaptation to geomorphological change: An empirical study in Cigu Lagoon, southwestern coast of Taiwan. *Front. Environ. Sci.* **2023**, *10*, 1091640. [CrossRef]
88. Thom, B.; Hudson, J.; Dean-Jones, P. Estuary contexts and governance models in the new climate era, New South Wales, Australia. *Front. Environ. Sci.* **2023**, *11*, 1127839. [CrossRef]
89. Wolanski, E.; Ducrotoy, J.-P. Estuaries of Australia in 2050 and beyond—A synthesis. In *Estuaries of Australia in 2050 and Beyond*; Springer: New York, NY, USA, 2014; pp. 1–13.
90. Nicholls, R.J.; Adger, W.N.; Hutton, C.W.; Hanson, S.E. (Eds.) *Deltas in the Anthropocene*; Springer Nature: Cham, Switzerland, 2020; p. 282.
91. Syvitski, J.; Anthony, E.; Saito, Y.; Z˘ainescu, F.; Day, J.; Bhattacharya, J.; Giosan, L. Large deltas, small deltas: Toward a more rigorous understanding of coastal marine deltas. *Glob. Planet. Change* **2022**, *218*, 103958. [CrossRef]
92. Overeem, I.; Syvitski, J.P.M. *Dynamics and Vulnerability of Delta Systems*; LOICZ Reports & Studies No. 35; GKSS Research Center: Geesthacht, Germany, 2009; p. 54.
93. Allison, M.; Yuill, B.; Toörnqvist, T.; Amelung, F.; Dixon, T.H.; Erkens, G.; Stuurman, R.; Jones, C.; Milne, G.; Steckler, M.; et al. Global risks and research priorities for coastal subsidence. *Eos* **2016**, *97*, 22–27. [CrossRef]
94. Törnqvist, T.E. A river delta in transition. *Nat. Sustain.* **2023**, *6*, 617–618. [CrossRef]
95. Coastal Protection and Restoration Authority of Louisiana (CPRA). *Louisiana's Comprehensive Master Plan for a Sustainable Coast*; Coastal Protection and Restoration Authority of Louisiana: Baton Rouge, LA, USA, 2017; p. 172.
96. Wright, L.D.; Wu, W. Pearl River Delta and Guangzhou (Canton) China. In *Tomorrow's Coasts: Complex and Impermanent*; Coastal Research Library Series; Wright, L.D., Nichols, C.R., Eds.; Springer: Cham, Switzerland, 2019; pp. 193–205.
97. Syvitski, J.P.M.; Kettner, A.J.; Hannon, M.T.; Hutton, E.W.H.; Overeem, I.; Brakenridge, G.R.; Day, J.; Vo, C.; Saito, Y.; Giosan, L.; et al. Sinking deltas. *Nat. Geosci.* **2009**, *2*, 681–686. [CrossRef]
98. Wang, J.; Muto, T.; Urata, K.; Sato, T.; Naruse, H. Morphodynamics of river deltas in response to different basin water depths: An experimental examination of the grade index model. *Geophys. Res. Lett.* **2019**, *46*, 5265–5273. [CrossRef]
99. Rantanen, M.; Karpechko, A.Y.; Lipponen, A.; Nording, K.; Hyvarinen, O.; Ruosteenoia, K.; Vihma, T.; Laaksonen, A. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* **2022**, *3*, 168. [CrossRef]
100. Wendisch, M.; Bruckner, M.; Burrows, J.; Crewell, S.; Dethloff, K.; Ebell, K.; Lupkes, C.; Macke, A.; Notholt, J.; Quaas, J.; et al. Understanding causes and effects of rapid warming in the Arctic. *Eos* **2017**, *98*. [CrossRef]
101. Arctic Monitoring and Assessment Program (AMAP). *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) Summary for Policy Makers*; Arctic Monitoring and Assessment Program: Oslo, Norway, 2017; p. 268.
102. Wright, L.D. The Alaskan Arctic Coast. In *Tomorrow's Coasts: Complex and Impermanent*; Coastal Research Library Series; Wright, L.D., Nichols, C.R., Eds.; Springer: Cham, Switzerland, 2019; pp. 261–273.
103. Douglas, D.C. *Arctic Sea Ice Decline: Projected Changes in Timing and Extent of Sea Ice in the Bering and Chukchi Seas*; U.S. Geological Survey Open-File Report 2010–1176; U.S. Geological Survey: Reston, VA, USA, 2010; p. 32.
104. Overeem, I.; Anderson, R.S.; Wobus, C.W.; Clow, G.D.; Urban, F.E.; Matell, N. Sea ice loss enhances wave action at the Arctic coast. *Geophys. Res. Lett.* **2011**, *38*, L17503. [CrossRef]

105. Buzard, R.M.; Kinsman, N.E.M.; Maio, C.V.; Erikson, L.H.; Jones, B.M.; Anderson, S.; Glenn, R.J.T.; Overbeck, J.R. Barrier Island reconfiguration leads to rapid erosion and relocation of a rural Alaska community. *J. Coast. Res.* **2023**, *39*, 625–642. [CrossRef]
106. Lawrence, D.M.; Slater, A.G.; Tomas, R.A.; Holland, M.; Deser, C. Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophys. Res. Lett.* **2008**, *35*, L11506. [CrossRef]
107. Underwood, E. Why are Arctic rivers rising in winter? *Eos* **2017**, *98*. [CrossRef]
108. Stepien, A.; Koivurova, T.; Gremsperger, A.; Niemi, H. Arctic Indigenous Peoples and the Challenge of Climate Change. In *Arctic Marine Governance: Opportunities for Transatlantic Cooperation*; Tedsen, E., Cavalieri, S., Kraemer, R., Eds.; Springer: Dordrecht, The Netherlands, 2014.
109. Poppick, L. Engineering new foundations for a thawing Arctic. *Eos* **2017**, *98*. [CrossRef]
110. Masselink, G.; Beetham, E.; Kench, P. Coral reef islands can accrete vertically in response to sea level rise. *Sci. Adv.* **2020**, *6*, eaay3656. [CrossRef]
111. Woodroffe, C.D.; Webster, J.M. Coral reefs and sea-level change. *Mar. Geol.* **2014**, *352*, 248–267. [CrossRef]
112. Kench, P.S.; Liang, C.; Ford, M.R.; Owen, S.; Aslam, M.; Ryan, E.; Turner, T.; Beetham, E.; Dickson, M.; Stephenson, W.; et al. Reef islands have continually adjusted to environmental change over the past two millennia. *Nat. Commun.* **2023**, *14*, 508. [CrossRef]
113. Sheppard, C.; Dixon, D.J.; Gourlay, M.; Sheppard, A.; Payet, R. Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. *Estuar. Coast. Shelf Sci.* **2005**, *64*, 223–234. [CrossRef]
114. Hughes, T.P.; Kerry, J.T.; Baird, A.H.; Connolly, S.R.; Dietzel, A.; Eakin, C.M.; Heron, S.F.; Hoey, A.S.; Hoogenboom, M.O.; Liu, G.; et al. Global warming transforms coral reef assemblages. *Nature* **2018**, *556*, 492–496. [CrossRef] [PubMed]
115. Marzonie, M.R.; Bay, L.K.; Bourne, D.G.; Hoey, A.S.; Matthews, S.; Nielsen, J.J.V.; Harrison, H.B. The effects of marine heatwaves on acute heat tolerance in corals. *Glob. Change Biol.* **2023**, *29*, 404–416. [CrossRef] [PubMed]
116. Australian Bureau of Meteorology. *2016 Marine Heatwave on the Great Barrier Reef*; Australian Bureau of Meteorology: St. Docklands, VIC, Australia, 2016; p. 2.
117. Bay, L.K.; Gilmour, J.; Muir, B.; Hardisty, P. Management approaches to conserve Australia's marine ecosystem under climate change. *Science* **2023**, *3381*, 631–636. [CrossRef]
118. Abelson, A.; Reed, D.C.; Edgar, G.J.; Smith, C.S.; Kendrick, G.A.; Orth, R.J.; Airoldi, L.; Silliman, B.; Beck, M.W.; Krause, G.; et al. Challenges for Restoration of Coastal Marine Ecosystems in the Anthropocene. *Front. Mar. Sci.* **2020**, *7*, 544105. [CrossRef]
119. Knowlton, N.; Grottoli, A.G.; Kleypas, J.; Obura, D.; Corcoran, E.; de Goeij, J.; Felis, T.; Harding, S.; Mayfield, A.; Miller, M.; et al. *Rebuilding Coral Reefs: A Decadal Grand Challenge*; International Coral Reef Society and Future Earth Coasts: Oakland, CA, USA, 2021. [CrossRef]
120. Pelling, M.; Blackburn, S. (Eds.) . *Megacities and the Coast: Risk, Resilience, and Transformation*; Routledge: London, UK, 2013; Volume 248, Available online: https://www.routledge.com/books/details/9780415815123/ (accessed on 15 August 2023).
121. Vorosmarty, C.J.; Melillo, J.M.; Wuebbles, D.J.; Jain, A.K.; Ando, A.W.; Chen, M.; Tuler, S.; Smith, R.; Kicklighter, D.; Corsi, F.; et al. Applying the framework to study climate-induced extremes on food, energy, and water systems (C-FEWS): The role of engineered and natural infrastructures, technology, and environmental management in the United States Northeast and Midwest. *Front. Environ. Sci.* **2023**, *11*, 1070144. [CrossRef]
122. Burnett, J. Billions Spent on Flood Barriers, but New Orleans Still a 'Fishbowl'. *NPR*. 2015. Available online: http://www.npr.org/2015/08/28/432059261/billions-spent-on-flood-barriers-but-new-orleans-still-a-fishbowl (accessed on 15 August 2023).
123. Hemmerling, S.A.; DeMyers, C.; Parfait, J.; Pinñero, E.; Baustian, M.M.; Bregman, M.; Di Leonardo, D.; Esposito, C.; Georgiou, I.Y.; Grismore, A.; et al. A community-informed transdisciplinary approach to coastal restoration planning: Maximizing the social and ecological co-benefits of wetland creation in Port Fourchon, Louisiana, USA. *Front. Environ. Sci.* **2013**, *11*, 1105671. [CrossRef]
124. Temmerman, S.; Meire, P.; Bouma, T.; Herman, P.; Ysebaert, T.; De Vriend, H.J. Ecosystem-based coastal defense in the face of global change. *Nature* **2013**, *504*, 79–83. [CrossRef]
125. Arkema, K.K.; Guannel, G.; Verutes, G.; Wood, S.; Guerry, A.; Ruckelshaus, M.; Kareiva, P.; Lacayo, M.; Silver, J. Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Chang.* **2013**, *3*, 3–913. [CrossRef]
126. Reguero, B.G.; Beck, M.W.; Bresch, D.N.; Meliane, I. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE* **2018**, *13*, e0192132. [CrossRef]
127. Calder, R.S.; Shi, C.; Mason, S.A.; Olander, L.P.; Borsuk, M.E. Forecasting ecosystem services to guide coastal wetland rehabilitation decisions. *Ecosyst. Serv.* **2019**, *39*, 101007. [CrossRef]
128. Livingston, J.; Woiwode, N.; Bortman, M.; McAfee, S.; McLeod, K.; Newkirk, S.; Murdock, S. Natural Infrastructure to Mitigate Inundation and Coastal Degradation. In *Tomorrow's Coasts: Complex and Impermanent*; Wright, L.D., Nichols, C.R., Eds.; Coastal Research Library, 27; Springer: Cham, Switzerland, 2019; pp. 167–189.
129. Thom, B. *Future challenges in beach management as contested spaces. Sandy Beach Morphodynamics*; Jackson, D.W.T., Short, A.D., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 711–731.
130. Hutton, N.S.; Allen, T.R. The role of traditional knowledge in coastal adaptation priorities: The Pamunkey Indian reservation. *Water* **2020**, *12*, 3548. [CrossRef]
131. Matthews, V.; Vine, K.; Atkinson, A.-R.; Longman, J.; Lee, G.; Vardoulakis, S.; Mohamed, J. Justice, culture, and relationships: Australian Indigenous prescription for planetary health. *Science* **2023**, *381*, 636–641. [CrossRef]

132. Ranasinghe, R. On the need for a new generation of coastal change models for the 21st century. *Sci. Rep.* **2020**, *10*, 2010. [CrossRef]
133. Wright, L.D.; Thom, B.G. Promoting Resilience of Tomorrow's Impermanent Coasts. In *Tomorrow's Coasts: Complex and Impermanent*; Wright, L.D., Nichols, C.R., Eds.; Coastal Research Library Series; Springer: Cham, Switzerland, 2019; pp. 341–353.